Geminal Diol Formation from the Interaction of a Ketone with Water in the Gas Phase: Structure and Reactivity of Cyclooctanone-(H$_2$O)$_{1,2}$ Clusters

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ABSTRACT. Hydration of ketones is known to occur in condensed phases, but is not considered to be favourable in the gas phase due to restricted water content. We report the first evidence of geminal diol formation upon ketone hydration in the gas phase, obtained through the investigation of the interactions of cyclooctanone with water using broadband rotational spectroscopy. Oxygen-atom exchange between water and cyclooctanone has been observed for two isomers of cyclooctanone-H$_2$O and two isomers of cyclooctanone-(H$_2$O)$_2$. All complexes have been unambiguously identified from the analysis of the rotational spectrum of the parent species and all their $^{13}$C and $^{18}$O isotopologues, and their heavy-atom substitution and effective structures have been determined as well as their binding interactions. Production of gem-diols from gas-phase hydration of ketones has implications for atmospheric chemistry and opens a new channel for secondary aerosol formation.

TOC GRAPHICS

Hydration • Rotational spectroscopy • Computational chemistry • Structural determination • Hydrogen bond.
The interactions of water with organic molecules have a tremendous importance in many chemical, physical and biological processes. The presence of water can change reaction outcomes, modify conformational preferences, and influence photochemistry and photophysics. Water is the third compound in abundance in our atmosphere, with 80% of its mass being in the troposphere, where the majority of atmospheric reactions take place. It is known that the presence of water influences the formation and evolution of secondary organic aerosol (SOA), although the precise mechanisms have not been elucidated yet. Water can compete with atmospheric oxidants such as OH radicals and ozone in their binding to volatile organic compounds (VOCs), thus changing the proportion of oxidised products and SOA composition. By forming non-covalent interactions with VOCs, water can act as a catalyst or inhibitor in atmospheric reactions, an effect observed even in binary complexes when only one water molecule is involved. Water complexes can also modify photochemical reactions and absorption of solar radiation. All the above has led to an increasing interest in water complexes of VOCs and their oxidised products.

Aldehydes and ketones are important oxidised species in the atmosphere, where they are directly released or are produced from the oxidation of other VOCs. They are involved in further oxidative reactions which eventually result in aerosol formation. Hydration of aldehydes and ketones is known to be extensive in condensed phases, but it was thought to be unfavourable in the gas phase due to limited water availability. However, gas-phase studies on the hydration of methylglyoxal and formaldehyde by infrared and UV spectroscopy and on acrolein-water complexes by rotational spectroscopy have provided new evidence of aldehyde hydration in the gas phase. The reaction occurs via the formation of geminal diols, reactive species with two hydroxyl groups bound to the same carbon atom. Direct evidence of a reversible reaction with water was obtained for methylglyoxal and formaldehyde though observation of the corresponding gem-diols,
while for acrolein\textsuperscript{19} indirect evidence was obtained from the enhanced abundance of acrolein’s \textsuperscript{18}O isotopologue in acrolein-water complexes when a H\textsubscript{2}\textsuperscript{18}O-enriched sample was used. \textit{Gem}-diols produced in the gas phase could be involved in atmospheric processes, and in fact several reactions have been proposed, with oxidation of \textit{gem}-diols to form carboxylic acids predicted to be the most favourable.\textsuperscript{20} It should be noted that the concentration of carboxylic acids in the troposphere is significantly underpredicted.\textsuperscript{21}

Further investigations to characterise complexes of aldehyde and ketones with water are desirable. An accurate physicochemical description of water complexes is accomplished using high resolution spectroscopic methods, which can provide a clear identification of the species involved and determine their structural parameters. Broadband rotational spectroscopy,\textsuperscript{22} with its strong dependence to even small changes in mass distribution, is ideally suited to discriminate different molecular systems simultaneously present in a sample, including different isotopologues of the same species. The acquisition of large swathes of spectrum facilitates the recognition of the unique line patterns produced by each existing species. Accurately determining the relative arrangement and structural features of water-containing complexes is necessary to understand the first steps of aggregation and to calculate thermodynamic properties such as free Gibbs energies.

Using broadband rotational spectroscopy, we have investigated the water complexes of cyclooctanone (CYO) and obtained the first experimental evidence of the formation of a \textit{gem}-diol upon hydration of a ketone in the gas phase. Two complexes of CYO-H\textsubscript{2}O and two of CYO-(H\textsubscript{2}O)\textsubscript{2} were identified, and for all of them \textit{gem}-diol formation was observed indirectly through oxygen atom exchange. CYO is an eight-membered ring ketone commonly used in the synthesis of large cyclic odorants,\textsuperscript{23,24} for which we have previously reported three conformations in the gas phase, two boat-chair (BC1, BC2) and one twisted boat-chair configurations (TBC1).\textsuperscript{25} CYO can be
produced from reactions of cyclooctane with OH radicals\textsuperscript{26} in the atmosphere. The rate constants of CYO reactions with OH radicals and Cl atoms have been measured.\textsuperscript{26,27}

The rotational spectrum of CYO with water in the 2-8 GHz frequency range was collected using our broadband rotational spectrometer.\textsuperscript{28,29} Once the lines from the observed conformers of CYO\textsuperscript{25} were removed from the spectrum, spectral patterns associated to other species emerged. Two isomers for CYO-H\textsubscript{2}O and another two isomers for CYO-(H\textsubscript{2}O)\textsubscript{2} were assigned. The measured transitions (SI) were fitted to the Watson A-reduced Hamiltonian in the I\textsuperscript{r} representation\textsuperscript{30} using Pickett’s programs\textsuperscript{31} to give the rotational and centrifugal distortion constants of Tables 1 and 2. To identify them, we predicted the lower-energy isomers of the complexes of CYO with one and two water molecules. We used the program CREST\textsuperscript{32} to explore the potential energy surfaces of the complexes and optimised the initial structures at B3LYP-D3BJ and MP2 levels of theory with the 6-311++G(d,p) basis set. All isomers were confirmed to be local minima by performing harmonic vibrational calculations. Their zero-point corrected energies, as well as dissociation energies using the counterpoise method\textsuperscript{33} and including fragment relaxation terms,\textsuperscript{34} were determined (Tables S1-S2, SI). Both B3LYP-D3BJ and MP2 methods agree in their predicted global minima and the general energy ordering, although there are some discrepancies for higher-energy complexes. Complexes involving CYO in conformations different from its lowest-energy conformer are \textit{ca.} 7 kJ mol\textsuperscript{-1} above the global minimum for both CYO-H\textsubscript{2}O and CYO-(H\textsubscript{2}O)\textsubscript{2}, indicating that the conformational preferences of CYO remain unchanged upon complexation with water.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>1w-I (BC1)</th>
<th>1w-II (BC1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>MP2</td>
</tr>
<tr>
<td>A (MHz)</td>
<td>1366.8386(12)</td>
<td>1363.6</td>
</tr>
<tr>
<td>B (MHz)</td>
<td>1025.83340(58)</td>
<td>1062.2</td>
</tr>
<tr>
<td>C (MHz)</td>
<td>873.02639(56)</td>
<td>900.9</td>
</tr>
<tr>
<td>Δλ (kHz)</td>
<td>1.139(21)</td>
<td>0.581</td>
</tr>
<tr>
<td>Δκ (kHz)</td>
<td>−2.906(35)</td>
<td>1.377</td>
</tr>
<tr>
<td>Δκ (kHz)</td>
<td>3.30(17)</td>
<td>−1.203</td>
</tr>
<tr>
<td>δλ (kHz)</td>
<td>0.0363(21)</td>
<td>0.025</td>
</tr>
<tr>
<td>δκ (kHz)</td>
<td>−0.174</td>
<td>−0.022</td>
</tr>
<tr>
<td>μa/μb/μc (D)</td>
<td>y/n/y</td>
<td>−1.80/2/−1.0</td>
</tr>
<tr>
<td>σ (kHz)</td>
<td>4.8</td>
<td>−</td>
</tr>
<tr>
<td>N</td>
<td>35</td>
<td>−</td>
</tr>
<tr>
<td>ΔE0 (cm⁻¹)</td>
<td>−</td>
<td>0.0</td>
</tr>
<tr>
<td>D₀ (kJ/mol)</td>
<td>−</td>
<td>22.8</td>
</tr>
</tbody>
</table>

a A, B and C are the rotational constants; Δλ, Δκ, Δκ, δλ, and δκ are the centrifugal distortion constants; μa, μb and μc are the values of the electric dipole moment components along the principal inertial axes in Debye. b Rms deviation of the fit. c Number of rotational transitions included in the fit. d Relative electronic energies including the zero-point correction. e Binding energies from BSSE calculations. f Standard error in parentheses in units of the last digit. g MP2 and B3LYP-D3BJ with 6-311++G(d,p) basis set.

Table 2. Experimental and theoretical spectroscopic constants of the observed isomers of cyclooctanone-(H₂O)₂.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>2w-I (BC1)</th>
<th>2w-IV (BC1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>MP2</td>
</tr>
<tr>
<td>A (MHz)</td>
<td>1151.47283(58)</td>
<td>1163.9</td>
</tr>
<tr>
<td>B (MHz)</td>
<td>697.99633(35)</td>
<td>707.2</td>
</tr>
<tr>
<td>C (MHz)</td>
<td>564.91587(37)</td>
<td>575.0</td>
</tr>
<tr>
<td>Δλ (kHz)</td>
<td>0.1767(48)</td>
<td>0.145</td>
</tr>
<tr>
<td>Δκ (kHz)</td>
<td>0.988(15)</td>
<td>−0.131</td>
</tr>
<tr>
<td>Δκ (kHz)</td>
<td>−0.592(43)</td>
<td>0.397</td>
</tr>
<tr>
<td>δλ (kHz)</td>
<td>0.0121(24)</td>
<td>0.003</td>
</tr>
<tr>
<td>δκ (kHz)</td>
<td>0.569(25)</td>
<td>0.345</td>
</tr>
<tr>
<td>μa/μb/μc (D)</td>
<td>y/n/y</td>
<td>1.6/0.2/−0.2</td>
</tr>
<tr>
<td>σ (kHz)</td>
<td>4.7</td>
<td>−</td>
</tr>
<tr>
<td>N</td>
<td>58</td>
<td>−</td>
</tr>
<tr>
<td>ΔE0 (cm⁻¹)</td>
<td>−</td>
<td>0.0</td>
</tr>
<tr>
<td>D₀ (kJ/mol)</td>
<td>−</td>
<td>53.0</td>
</tr>
</tbody>
</table>
\(^a\) \(A\), \(B\) and \(C\) are the rotational constants; \(\Lambda_J\), \(\Lambda_{JK}\), \(\Lambda_K\), \(\delta_J\) and \(\delta_K\) are the centrifugal distortion constants; \(\mu_a\), \(\mu_b\) and \(\mu_c\) are the values of the electric dipole moment components along the principal inertial axes in Debye. \(^b\) Rms deviation of the fit. \(^c\) Number of rotational transitions included in the fit. \(^d\) Relative electronic energies including the zero-point correction. \(^e\) Binding energies from BSSE calculations. \(^f\) Standard error in parentheses in units of the last digit. \(^g\) MP2 and B3LYP-D3BJ with 6-311++G(d,p) basis set.

The observed species can be identified through comparison of the theoretical and experimental rotational constants, and consideration of the observed intensities of measured transitions with respect to the predicted dipole moment components. Definite confirmation was obtained from the observation of all the \(^{13}\)C and \(^{18}\)O isotopologues at the predicted frequency shifts. Using the differences between the moments of inertia of the parent species and each isotopologue (Table S3), the coordinates of the substituted atoms in the principal inertial axis system were determined using Kraitchman’s equations,\(^{35}\) and compared with those predicted theoretically (Fig. S2 and Tables S4-S7, SI). The observed complexes of CYO-H\(_2\)O were thus identified as 1w-I and 1w-II, and those of CYO-(H\(_2\)O)\(_2\) as 2w-I and 2w-IV. Higher energy complexes of CYO-(H\(_2\)O)\(_{1,2}\), including those where CYO is not in the lowest-energy conformation, were searched for in the spectrum but they could not be assigned. This could be due to their low population in our supersonic jet, owing to the significantly lower abundance of these conformations of CYO\(^{25}\) and the higher relative energies of these complexes.

The relative abundances of the mono- and dihydrates were estimated considering common \(a\)-type transitions and relating the observed intensity to the square of the MP2 \(a\)-dipole moment and the number density of the species. 1w-I was found to be 2.7 times more abundant than 1w-II, and 2w-I 1.3 times more abundant than 2w-IV. The latter result is not in agreement with the relative and binding energies of the dihydrates. However, the values above can be affected by collisional relaxation from higher-energy species in the supersonic jet.\(^{36}\) For example, 2w-III, 2w-V, 2w-IX and 2w-X could relax to 2w-IV.
The $^{13}$C isotopologues were observed in their natural abundance (1.1%), while the $^{18}$O isotopologues were observed by using a 1:1 mixture of H$_2^{18}$O and H$_2^{16}$O. Interestingly, the spectrum of the $^{18}$O species corresponding to the carbonyl oxygen of CYO was not observed in natural abundance (0.2%) in the pure H$_2^{16}$O spectrum but it was observed in the mixed H$_2^{18}$O:H$_2^{16}$O spectrum for all complexes. This phenomenon was previously observed in acrolein-water complexes.$^{19}$ It indicates that an exchange reaction between $^{16}$O and $^{18}$O occurs in the supersonic jet via geminal diol formation, a reversible reaction that involves addition of water to a ketone or an aldehyde (Scheme 1). The fact that the $^{18}$O lines show significantly larger intensity than those of the $^{13}$C species (Fig. 1) indicates that the reaction occurs extensively. Similarly to Li et al.,$^{19}$ we believe that the reaction happens in the gas phase, as CYO and water are kept separate up to the expansion point, at the throat of the nozzle. A surface reaction, catalysed by metals, could also take place, but it is unlikely as all surfaces are made from stainless steel in our setup.
Figure 1. $4_{0.4} \leftarrow 3_{0.3}$ rotational transition of parent 1w-II (top) and 2w-IV (bottom) and their heavy atom isotopologues, showing the emergence of the $^{18}$O isotopologue of the cyclooctanone ring when enriched H$_2^{18}$O water (red trace) was used to record the spectrum.
Gem-diols are usually unstable because the reaction is normally favoured towards the ketone (Scheme 1). However, we predicted the lower-energy structures of 1,1-cyclooctanediol using CREST and optimised them using B3LYP-D3BJ and MP2 methods (Table S8, SI). The lowest-energy 1,1-cyclooctanediol has a boat-chair conformation and the gem-diol group at a corner position. We searched repeatedly for this species in our spectrum, but we could not find it. This could be due to the low magnitude of its dipole moment components or to its low population in the molecular jet. Moreover, the reaction may happen at a rate faster than our experimental timescale.

Scheme 1. Geminal diol formation, reversible reaction.

We explored the thermochemistry of the reaction at 0 K and at 346 K, the temperature at which CYO was heated in our experiment, and show the results in Fig. 2 and the SI. Similarly to what was predicted for acrolein-water, formation of the complexes from CYO and water is thermodynamically favourable at 0 K, but unfavourable at 346 K. The same applies to formation of the gem-diols for both CYO-H\textsubscript{2}O and CYO-(H\textsubscript{2}O)\textsubscript{2}. There is a large barrier (>120 kJ mol\textsuperscript{-1}) to the transition states from the water complexes, but it decreases substantially, by 50-60 kJ mol\textsuperscript{-1} depending on the temperature, upon addition of one water molecule. Significant stabilisation of transition states by hydrogen-bonding of one water molecule have been reported for acrolein, one isomer of oxalic acid, and other molecular systems including radicals.
Figure 2. Hydration reaction coordinates for cyclooctanone, showing the relative free energies at 0 K and 346 K (1 atm) at MP2/6-311++G(d,p), considering complexes with one (top) and two (bottom) water molecules.
The observation of all heavy-atom isotopologues of the CYO-(H₂O)₁₂ complexes allowed the determination of their experimental structures. From the coordinates of the substituted atom in the principal inertial axis system, the $r_s$ substitution bond lengths and angles are obtained. Alternatively, a least-squares fit of all the experimental moments of inertia for each complex yields their effective $r_0$ structures in the ground vibrational state (see Tables S9-S10, SI).³⁷ The $r_s$ structures show some C–C bond lengths that are considerably different from the expected 1.54 Å for sp³ hybridized carbon bonds, which can be attributed to the carbon atoms having imaginary coordinates or to the large errors of some coordinates (Tables S4-S7, SI). The $r_0$ structural parameters show more consistent values, and they agree well with those of the most abundant conformer of bare CYO, indicating that the structure of the ring does not significantly change upon complexation.
All complexes display O⋯H–O hydrogen bonds between water as a hydrogen bond donor and the carbonyl oxygen of CYO, and secondary C⋯H–O interactions between the lone pairs of the water oxygen and the hydrogens in CYO. In the complexes with two water molecules there are also O⋯H–O hydrogen bonds between the water molecules. This can be visualised using the non-covalent interaction (NCI) method, which is based on the electron density and its derivatives (Fig. 3).38

**Figure 3.** Observed complexes of cyclooctanone-(H₂O)₁₂ showing their NCI isosurfaces (s = 0.5) for values of \( \text{sign}(\lambda₂)\rho \) from −0.025 to +0.025 a.u. Blue indicates strong attractive interaction; green indicates weak attractive interaction; and red indicates strong repulsive interaction. The intermolecular interaction distances at MP2/6-311++G(d,p) level of theory are also shown.
Considering the MP2/6-311++G(d,p) structures, the primary hydrogen bonds for the monohydrates are very similar (Fig. 3). The difference lies in the secondary interactions. **1w-I** displays a C···H–O hydrogen bond much shorter than the two of **1w-II**, which are on the limit of the sum of the van der Waals radii of C and H.\(^{39}\) Looking at the NCI plots, it is possible to see additional attractive interactions in **1w-I** between the water oxygen and the CYO hydrogens. Secondary interactions may thus play a relevant stabilising role in **1w-I** rendering it the global minimum at MP2 and B3LYP-D3BJ levels of theory. **1w-I** also has higher abundance in our supersonic jet than **1w-II**. However, binding energies are predicted consistently higher for **1w-II**.

The hydrogen bond lengths of CYO-H\(_2\)O are similar to those determined experimentally for cyclohexanone-H\(_2\)O\(^{40}\) and cyclobutanone-H\(_2\)O.\(^{41}\) Energy decomposition analysis of CYO-H\(_2\)O from symmetry-adapted perturbation theory (SAPT)\(^{42}\) using Psi4\(^{43}\) shows that electrostatic interactions are about four times greater than dispersion forces (Table S11, SI). This result agrees with values obtained for other ketone-water complexes.\(^{40}\)

The dihydrates have practically identical O···H–O bond lengths, differing in the C···H–O hydrogen bonds involving the second water molecule. **2w-I** shows two C···H–O hydrogen bonds of 2.51 Å and 2.52 Å while **2w-IV** shows one C···H–O hydrogen bond of 2.45 Å. Both dihydrates display additional long attractive secondary interactions. The effects of hydrogen bond cooperativity\(^{44,45}\) are manifest in the shortening of the hydrogen bond and O···O distances for both dihydrates with respect to the monohydrates (Tables S9-S10, SI). The O···O distances are also shorter than that of \(2.98(4)\) Å of the water dimer.\(^{46}\)

Water molecules show a remarkable plasticity to adapt their arrangements around a substrate. In CYO-water complexes, this is manifest in the striking change of position of the carbonyl-binding
water molecule in going from $\textbf{1w-I}$ to $\textbf{2w-I}$, and in the changes in the angle $\angle \text{H}_w\text{O=C}$ from 112.2° ($\textbf{1w-I}$) to 125.1° ($\textbf{2w-I}$), and 116.6° ($\textbf{1w-II}$) to 125.6° ($\textbf{2w-IV}$). These changes may be necessary to optimise water-water and water-substrate interactions.

In summary, we have completely characterised the complexes of CYO with one and two water molecules, determining their structure and binding interactions. We report, to our knowledge, the first evidence of ketone hydration in the gas phase via $\text{gem}$-dial formation. Formation of $\text{gem}$-diols from CYO and water is predicted to be favourable at 0 K. This observation, together with those involving gas-phase $\text{gem}$-dial formation from aldehydes, suggest that hydration reactions of carbonyl-containing compounds are more common in the gas phase than originally believed. Formation of $\text{gem}$-diols in the atmosphere opens a new channel for the aggregation and reaction pathways of oxidised VOCs, and modifies the composition and properties of atmospheric organic material. $\text{Gem}$-diols have different interactions, reactions and photochemistry than carbonyl compounds.

A sound knowledge of the complex atmospheric chemistry arising from oxidised VOCs requires further investigation of the role of water, and of water complexes of atmospheric compounds. This in turn will help improve current models of SOA.

**Supporting Information.** Experimental methods, computational methods, lists of rotational transitions, and details of spectroscopic analyses.

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Notes

The authors declare no competing financial interests.

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